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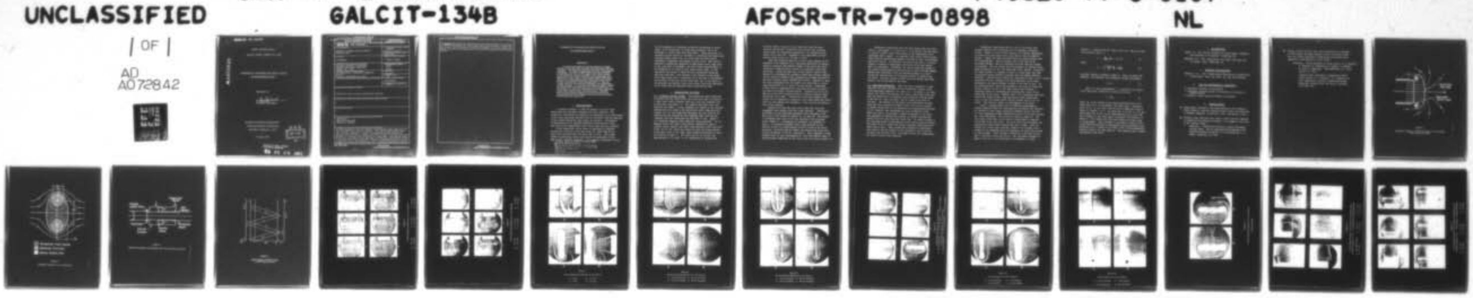

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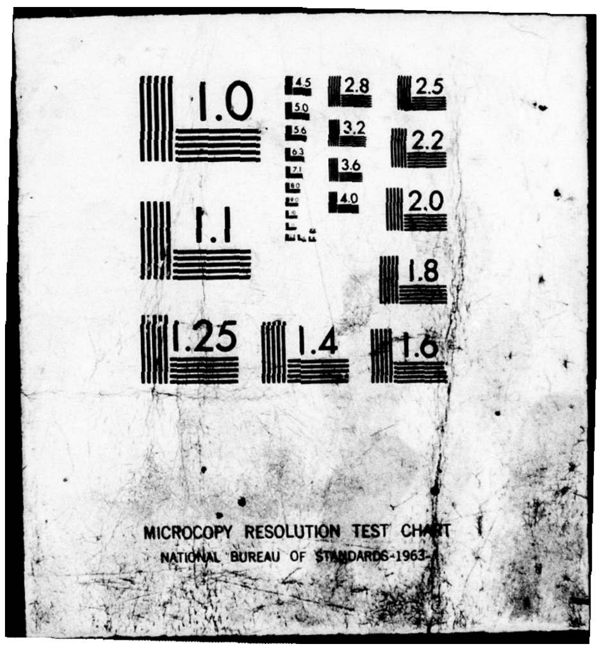
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DYNAMICS OF VORTICES AND SHOCK WAVES IN NONUNIFORM MEDIA

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A research program to study the dynamics of high-energy vortex rings with very thin rotational cores has been continued. The rings are generated by shock-tube and pulse techniques. A series of experiments has been conducted to determine the effect of the length of the driver section of the shock-tube vortex generator on the properties and behavior of vortex rings. (Varying the length of the shock-tube driver is the same thing as varying the piston stroke of more conventional vortex ring generators.) The use of ultra-short drivers has been attempted and preliminary results obtained. A retraction mechanism to rapidly

retract the mouth of the tube away from the vortex shortly after it is produced, to aid in the development of vortices generated by the ultra-short drivers, has been tested. With this device the velocity (strength) of vortices produced with several different driver lengths (but not yet the ultra-short drivers) has been measured.

DYNAMICS OF VORTICES AND SHOCK WAVES IN NONUNIFORM MEDIA

ABSTRACT

A research program to study the dynamics of high-energy vortex rings with very thin rotational cores has been continued. The rings are generated by shock-tube and pulse techniques. A series of experiments has been conducted to determine the effect of the length of the driver section of the shock-tube vortex generator on the properties and behavior of vortex rings. (Varying the length of the shock-tube driver is the same thing as varying the piston stroke of more conventional vortex ring generators.) The use of ultra-short drivers has been attempted and preliminary results obtained. A retraction mechanism to rapidly retract the mouth of the tube away from the vortex shortly after it is produced, to aid in the development of vortices generated by the ultra-short drivers, has been tested. With this device the velocity (strength) of vortices produced with several different driver lengths (but not yet the ultra-short drivers) has been measured.

1. INTRODUCTION

A research program to study the dynamics of vortex rings using shock-tube and pulse techniques has been continued. The project has concentrated on exploratory investigations of the performance of the vortex-generating apparatus and the interaction with the apparatus of the vortices during the early stages of formation. Development of instrumentation for obtaining quantitative measurements of the flow field in the neighborhood of the vortex rings has also continued.

In the experiments vortex rings are generated by impulsive acceleration of the air at the open mouth of a shock tube by the shock wave generated when the shock tube is fired. This unique method of generating vortex rings permits the generation of very high energy, turbulent structures. The program is designed to focus on the mechanisms of turbulence production and damping in vortex rings, on the mechanisms of vortex-ring instability, and on the interaction of vortex rings with solid bodies. These processes are currently of great interest in the effort to understand how large-scale, coherent motions which occur in vortex rings and shear layers contribute to dissipation and mixing at small scales. The work is directed at studying the properties of high-energy vortex rings prior to the occurrence of instability, and also certain characteristics of the instability as it occurs in very strong vortex rings. In this connection, two issues on which we have concentrated during the past year have been i) the question of the influence of the length of the slug of gas that is accelerated out of the tube on the thickness and structure of the core of the vortex ring, and ii) the effect on the structure and behavior of the vortex ring of the early interaction of the vortex with the apparatus used to generate the ring.

2. DESCRIPTION OF WORK

2.1 Variation of driver length. Surrounding the slug of fluid that is ejected from the mouth of the open shock tube after it is fired is a shear layer which eventually rolls up to form the rotational core of the vortex ring (figure 1). The length of this shear layer and therefore the radius a of the rotational core (figure 2) are obviously determined by the length of the shock-tube's driver (high pressure) section, for it is this length that determines the time delay at the mouth of the tube between the flow-initiating shock wave and the expansion wave that decelerates the fluid back to rest. Figure 3 is a schematic diagram of the shock-tube vortex generator. An x-t diagram of the wave field in this device, idealized for weak or acoustic waves, together with plots of the pressure at the end of the driver (on the left, where the velocity is zero) and of the velocity at the open mouth (on the right, where ideally the pressure is zero) are sketched in figure 4. The shock tube is 7.2 cm dia. and approximately 1.6 m long. In our experiments we measure the pressure history at point A in the shock tube with fast-time-response piezoelectric transducers and from the data calculate, using simple one dimensional gasdynamics, the detailed velocity history at the open end. Typically in our experiments the time between points B and C is of order 10 msec.

Since the dynamical behavior of vortex rings depends on the thickness of the rotational core, interesting differences in behavior should be observed with different lengths of the shock-tube driver, equivalent to different piston strokes in conventional vortex-ring generators. During the past year we have begun a study of this question by investigating the qualitative differences between different drivers using the schlieren flow visualization technique described in last year's interim report (AFOSR-TR-78-1403). Figures 5-7 show the early development near the mouth of the shock tube of vortex rings generated by 2.5, 5 and 15 cm long drivers, respectively. In this series of experiments the retracting tube shown in figure 3 was fixed in the fully retracted position. Indicated in each of the figures are the times measured from an arbitrary origin at which the pictures were taken. Visualization of the flow outside of the vortex core is enhanced by cooling the walls of the shock tube before each run; this explains the asymmetric "wisp" seen at the bottom of most of the pictures.

Figures 8-10 show the same vortex rings after they have propagated some distance from the vortex generator. Particularly noteworthy are the sinusoidal instabilities seen developing on the thin cores of the vortices in figures 9c, 10c and 10f. The number of instability waves seen on the core decreases with increasing driver length (i.e., increasing core diameter), as predicted by theory. A comparison between vortex rings produced by four different drivers at a fixed distance from the mouth of the vortex generator, visualized with and without precooling of the shock tube, is given in figures 11 and 12, respectively. Some suggestive results obtained while we were investigating the effect that different types of instrumentation might have on the vortex rings are shown in figure 13.

Preliminary experiments have also been made using very short drivers, with lengths L = 0 and 1 cm. In the former case the driver is actually of finite volume only because of the deformation of the diaphragm before rupture. As expected, these drivers yield vortices whose behavior progressively departs from that of more conventionally generated vortices. In particular, the vortex from the L = 0 driver appears to undergo an interaction with the lip of the tube shortly after it is generated. Thereafter, its core is much less visible in the schlieren photographs and its structure is much less well defined. Whether this interaction is the one discussed below or is more specifically characteristic of low-energy vortices (or both) is not yet known. Pictures of these vortices and more details about their behavior will be presented in the future.

2.2 Retraction Mechansim. When one tries to generate a vortex ring with very thin rotational core by keeping the "stroke" of the vortex-generating apparatus very short, i.e., by having a very short driver, the vortex ring remains very close to the mouth of the tube after the pulsed flow is terminated, and it interacts with the walls of the tube (or, more precisely, with its image in the walls of the tube). The influence of this effect on the generation of vortex rings has been discussed by Didden (1979), but was first noticed by student researchers in our laboratory and communicated privately to P.G. Saffman, thus stimulating the work of Sheffield (1977). Some time ago we incorporated a unique mechanism in our shock-tube apparatus to alleviate this problem by rapidly retracting the mouth of the tube away from the vortex ring. As shown in figure 3, the retracting mouth is pneumatically driven with pressurized helium. The mouth is set in motion and reaches maximum speed before the shock tube is fired. Only recently have preliminary experiments been made to test the function of this mechanism, and it still has not been used with the 0 and 1 cm length drivers, the configurations for which it will be most important.

Preliminary experiments with 2.5 and 10 cm drivers have already exhibited some interesting and not altogether anticipated results. Figures 14 and 15 show sequences of schlieren photographs of vortices near the mouth of the shock tube for the two different drivers. Figure 14a shows the field before the shock emerges from the retracting tube. The new feature here is the wake of the retracting cylinder, which is visualized very well when the cylinder is precooled. One can clearly see the formation of a Karman vortex sheet downstream of, say, the lower edge of the cylinder. Therefore, the wake consists of a sequence of pairs of vortex rings, the rings in each pair having vorticity of opposite sign and slightly different diameters. Each of these vortices has circulation of order 4×10^{-2} m^2/sec, only about 1% of the strength of the shock-generated vortex rings; furthermore, the space-averaged vorticity in the wake is zero. As the shock-generated vortex ring propagates away from the shock-tube mouth in figures 14 and 15, the wake vortex street provides a convenient means for visualizing the stretching that occurs in the strain field of the vortex. Whether there is any significant interaction between the weakest vortex rings generated in these experiments (e.g., by the zero-length driver) and the cylinder wake is not yet known. This will be a matter for investigation in the future.

From a carefully-timed series of schlieren photographs of vortices generated while the retracting-tube mechanism was operating, the velocity of vortex rings produced by different drivers (all with the same diaphragm initially separating the driver and driven sections) has been determined. The results are shown in figure 16. The rms scatter of the data in this series of experiments is indicated by the size of the error bars. As can be seen from the figure, the ring velocity varies nearly linearly with driver length. Since the velocity of a vortex ring is directly related to its strength, these results tell us something about the dependence of vortex-ring strength on driver length. If the strength is defined to be the total circulation Γ about the vortex ring core in, say, the upper half-plane of figure 2 and $\Gamma(s)$ is the distribution of circulation vs. radial distance s outward from the center of the core, then the vortex ring velocity is given by

$$U = \frac{\Gamma}{4\pi R}(\ln 8 - \tfrac{1}{2} + Z) \, , \qquad (1)$$

where

$$Z = \int_0^a \frac{\Gamma^2(s)}{\Gamma^2} \frac{ds}{s} - \ln(\frac{a}{R}) \, , \qquad (2)$$

and other notation is defined in figure 2. Thus, for fixed ring diameter, core diameter and normalized vorticity distribution,

$$U \propto \Gamma \, . \qquad (3)$$

Now, to a first approximation Γ is simply the circulation of the shear layer shed from the mouth of the tube

$$\Gamma \doteq u_2 \ell \, , \qquad (4)$$

where u_2 is the velocity of the shock-accelerated fluid in the shock tube and ℓ is the length of the shear layer. Therefore, since $\ell \propto L$, if u_2 = const. then (3) and (4) imply the result of figure 14, namely, $U \propto L$. In actual fact a, R and u_2, and also presumably both $\Gamma(s)/\Gamma$ and the approximation in (4), vary with driver length, so one would expect a departure from linearity in figure 16. The results show that these effects are either small or compensating. This conclusion is qualitatively similar to the result obtained previously in experiments using conventional vortex generators (e.g., equation 10 of Didden 1979), but the quantitative behavior seems to be quite different. This question will be further investigated in the future.

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Didden, N. 1979 "On the Formation of Vortex Rings: Rolling-up and Production of Circulation." ZAMP 30, 101.

Sheffield, J.S. 1977 "Trajectories of an ideal vortex pair near an orifice." Phys. Fluids 20, 543.

4. WRITTEN PUBLICATIONS

Kulkarny, V.A. 1978 "Experimental Observations of Slender-Core Vortex Rings." Bull. Am. Phys. Soc. 23, 988 (Abstract).

5. LIST OF PROFESSIONAL PERSONNEL

B. Sturtevant, Professor of Aeronautics

L. Hesselink, Research Fellow in Aeronautics and Lecturer in Applied Physics

V. Kulkarny, Senior Research Fellow in Aeronautics

6. INTERACTIONS

- Spoken paper presented at the Annual Meeting of the Division of Fluid Dynamics, American Physical Society, held at the University of Southern California, 19 November 1978. See Section 4 above.

- Results of this work have been useful in other research conducted at Caltech by the principal investigator, for example in work cited in the reference below.

  Reference : "Subharmonic Nonlinear Acoustic Resonances in Open Tubes. Part II: Experimental Investigation of the Open-End Boundary Condition" by B. Sturtevant and J. J. Keller, ZAMP 29, 473 (1978).

- Results of this work have been used productively by researchers at TRW Defense and Space Systems Group in the study of fluid flow and acoustic attenuation in high-energy gas-flowing lasers supported by DOE/Division of Laser Fusion.

  References: "Fluid Mechanics of Fusion Lasers" by J. Schwartz, V. Kulkarny, D. Ausherman, H. Legner, H. Bobitch, K. Yano, B. Sturtevant. TRW DSSG Rept. No. 33578-6001-RV-01 (1979).

  "Pressure Wave Attenuation in Repetitively Pulsed Fusion Lasers" by J. Schwartz, V.A. Kulkarny and D.R. Ausherman, presented at XIIth International Symposium on Shock Tubes and Waves, Jerusalem, 16-19 July 1979.

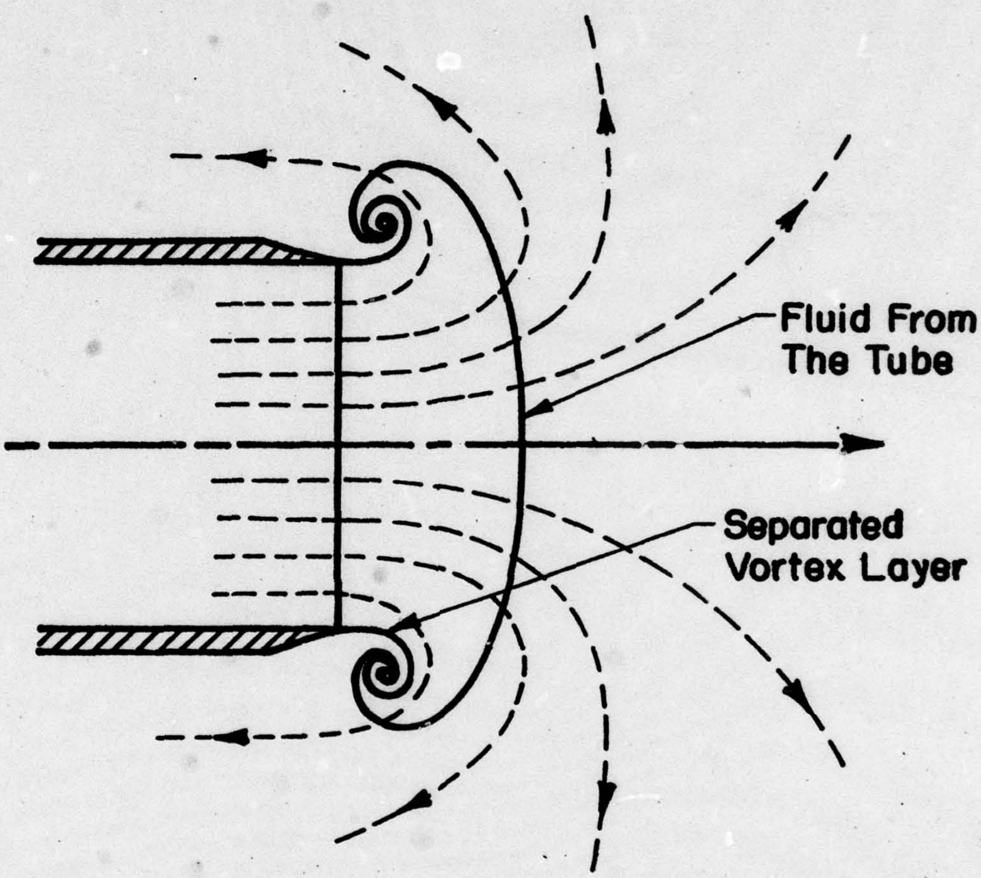

Figure 1

Schematic Diagram of the Formation of a Vortex Ring at the Mouth of a Tube

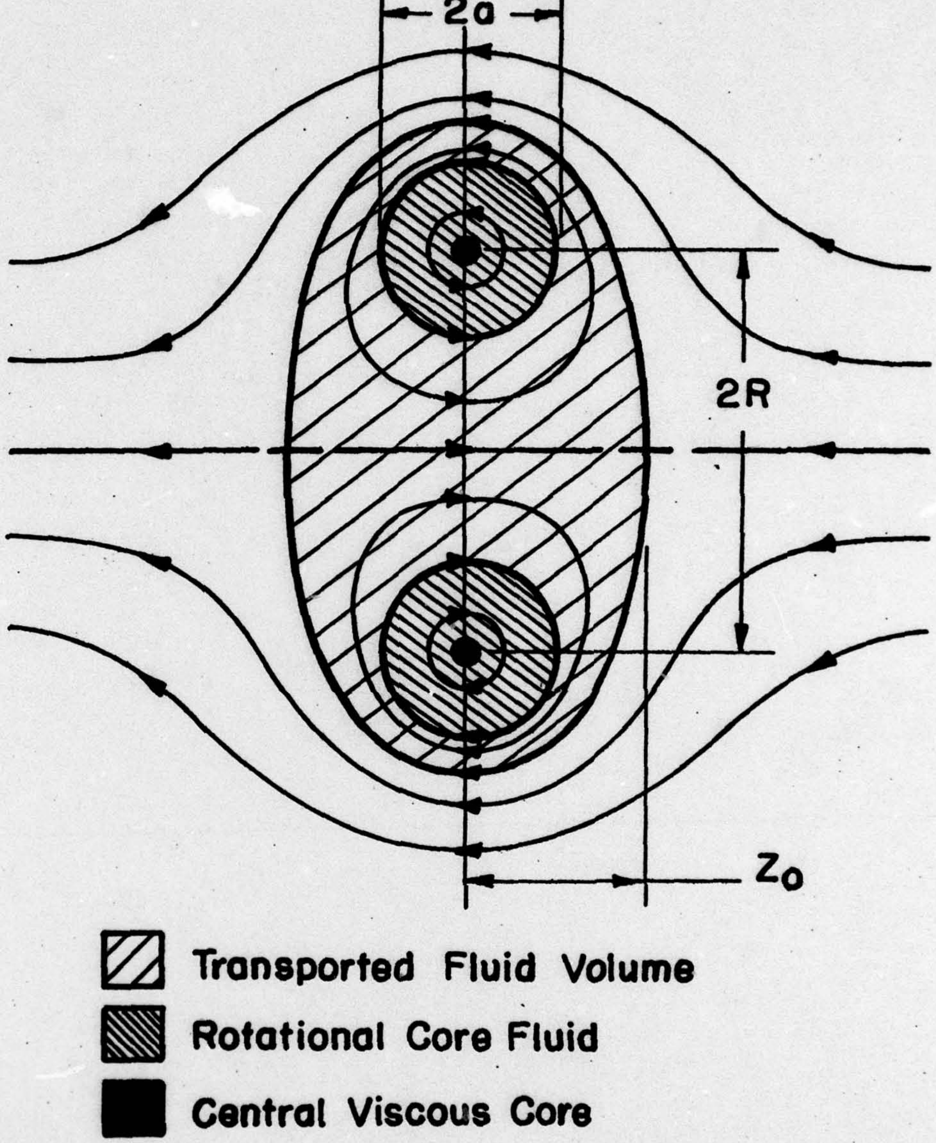

Figure 2

Schematic Diagram of a Vortex Ring

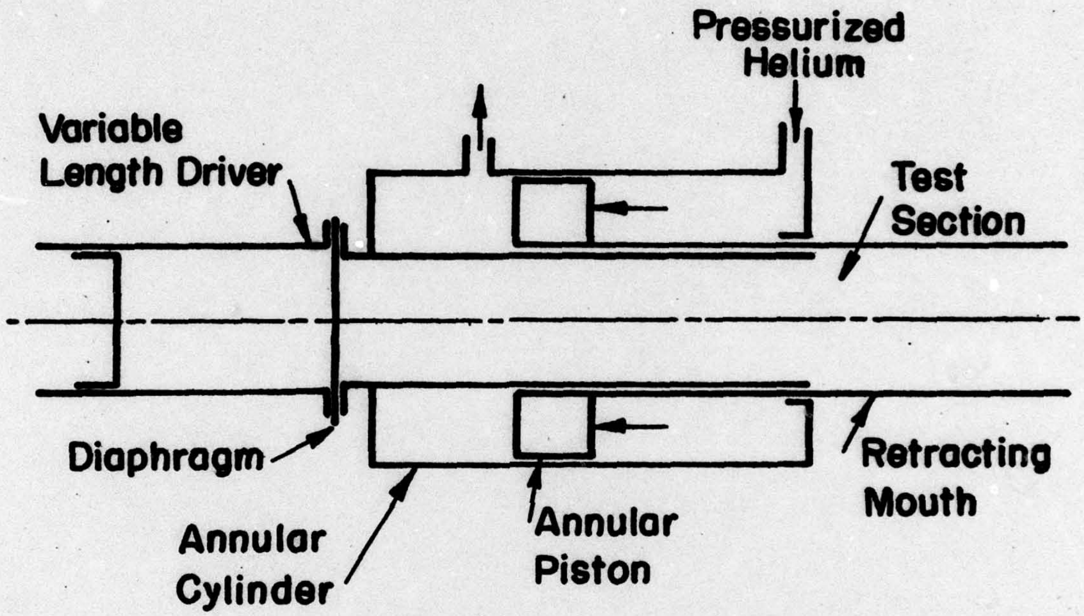

Figure 3

Schematic Diagram of the Shock Tube Vortex Ring Generator

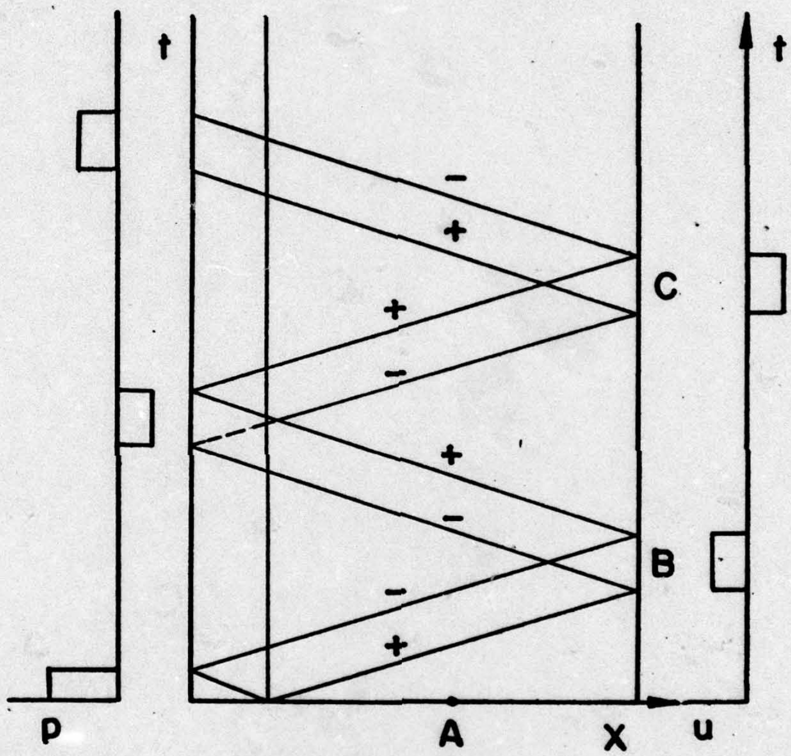

Figure 4

Wake Diagram of Shock-Tube Vortex Ring Generator

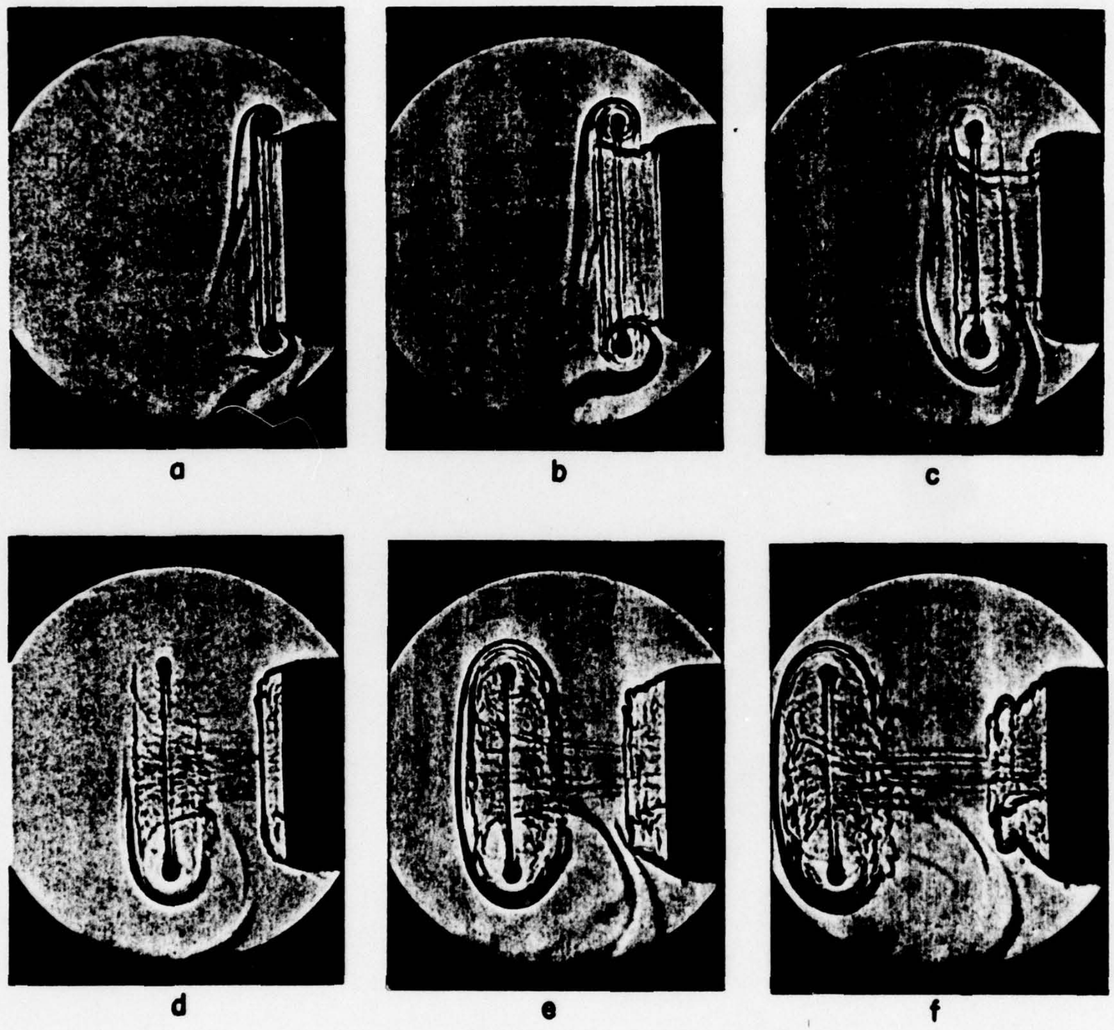

Figure 5

Vortex Ring Generated by 2.5 cm Driver

a. 4.5 ms b. 5.0 ms c. 5.5 ms

d. 6.5 ms e. 7.5 ms f. 8.5 ms

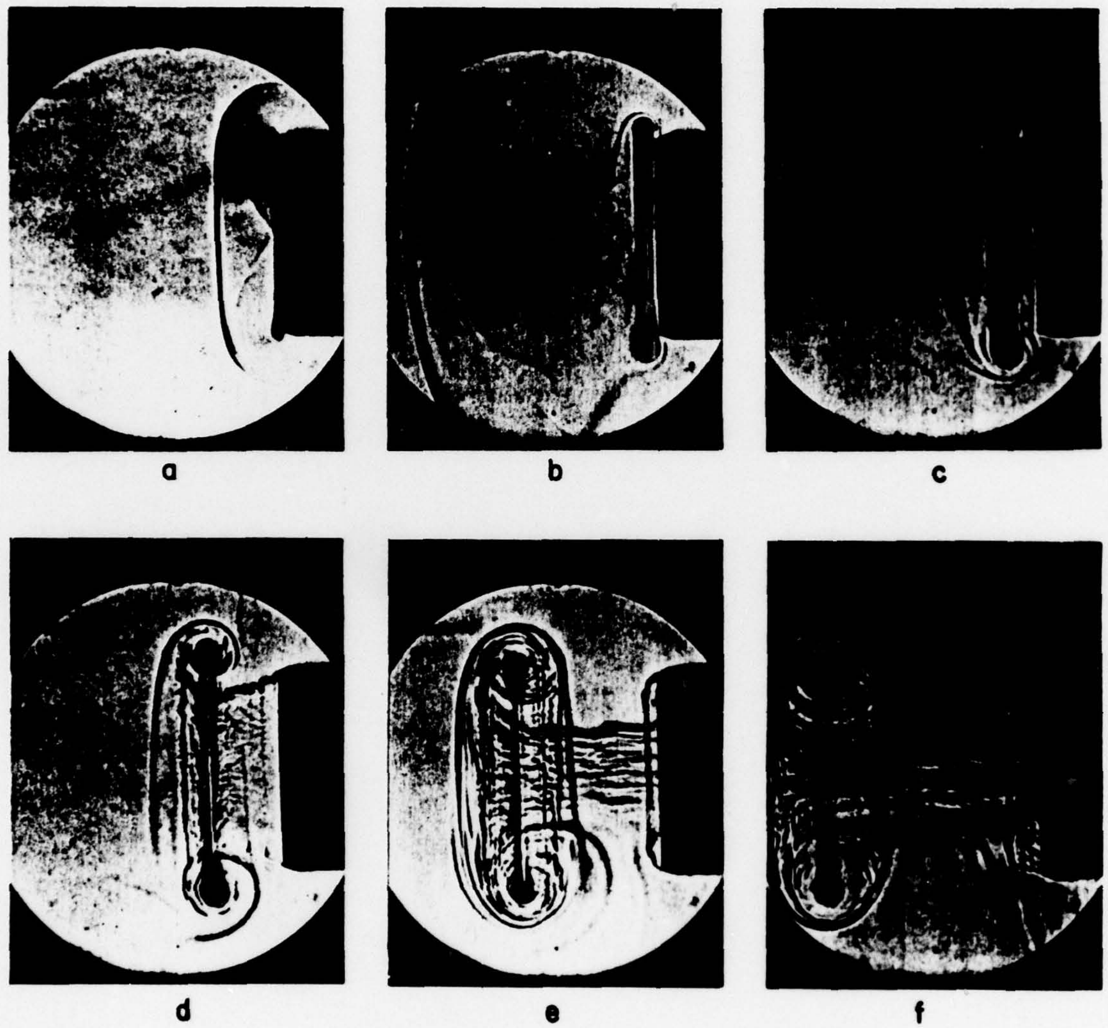

Figure 6

Vortex Ring Generated by 5.0 cm Driver

a. 4.0 ms	b. 4.2 ms	c. 4.5 ms
d. 5.0 ms	e. 6.0 ms	f. 7.0 ms

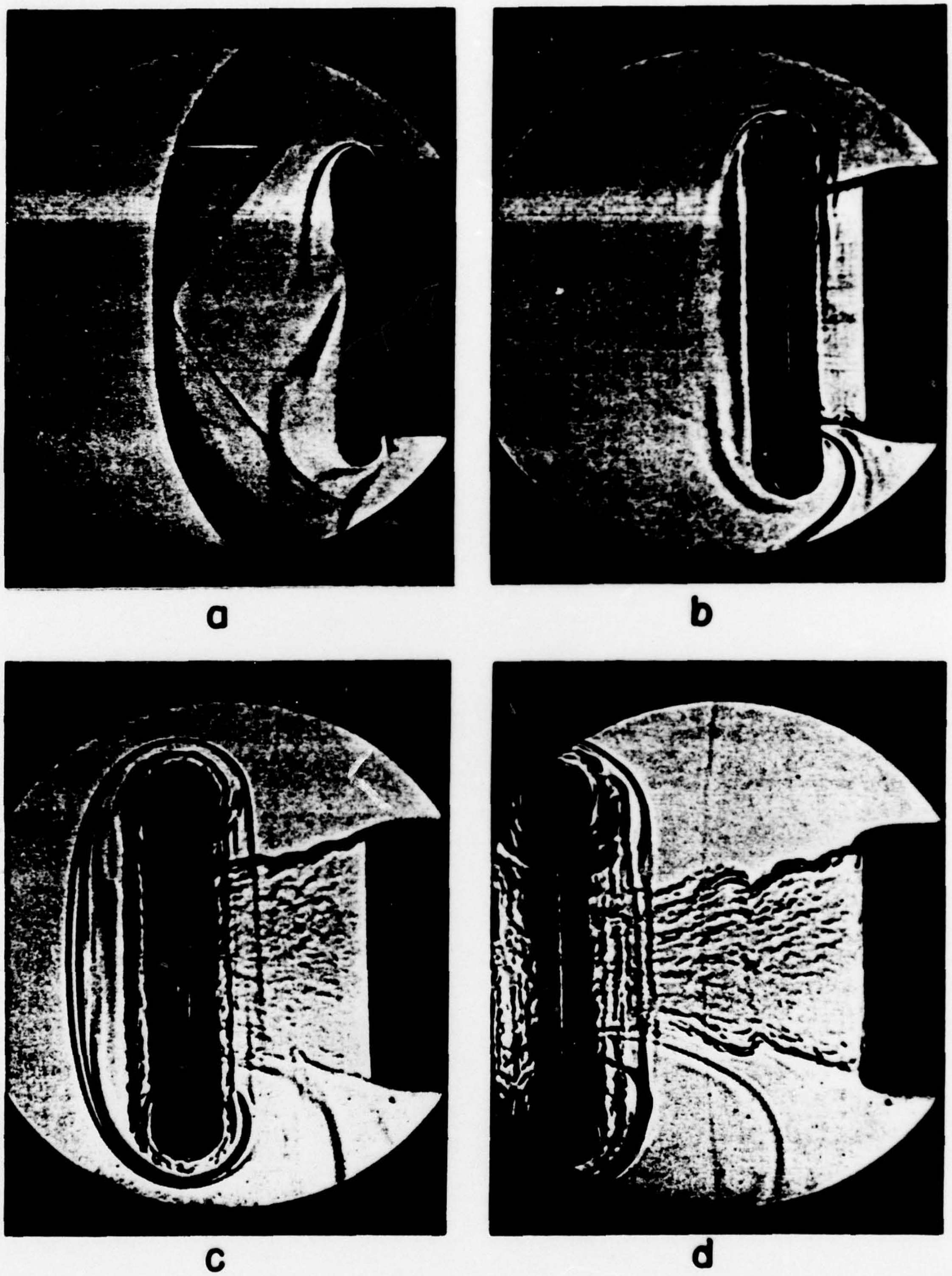

Figure 7

Vortex Ring Generated by 15 cm Driver

a. 4 ms b. 4.5 ms

c. 5 ms d. 5.5 ms

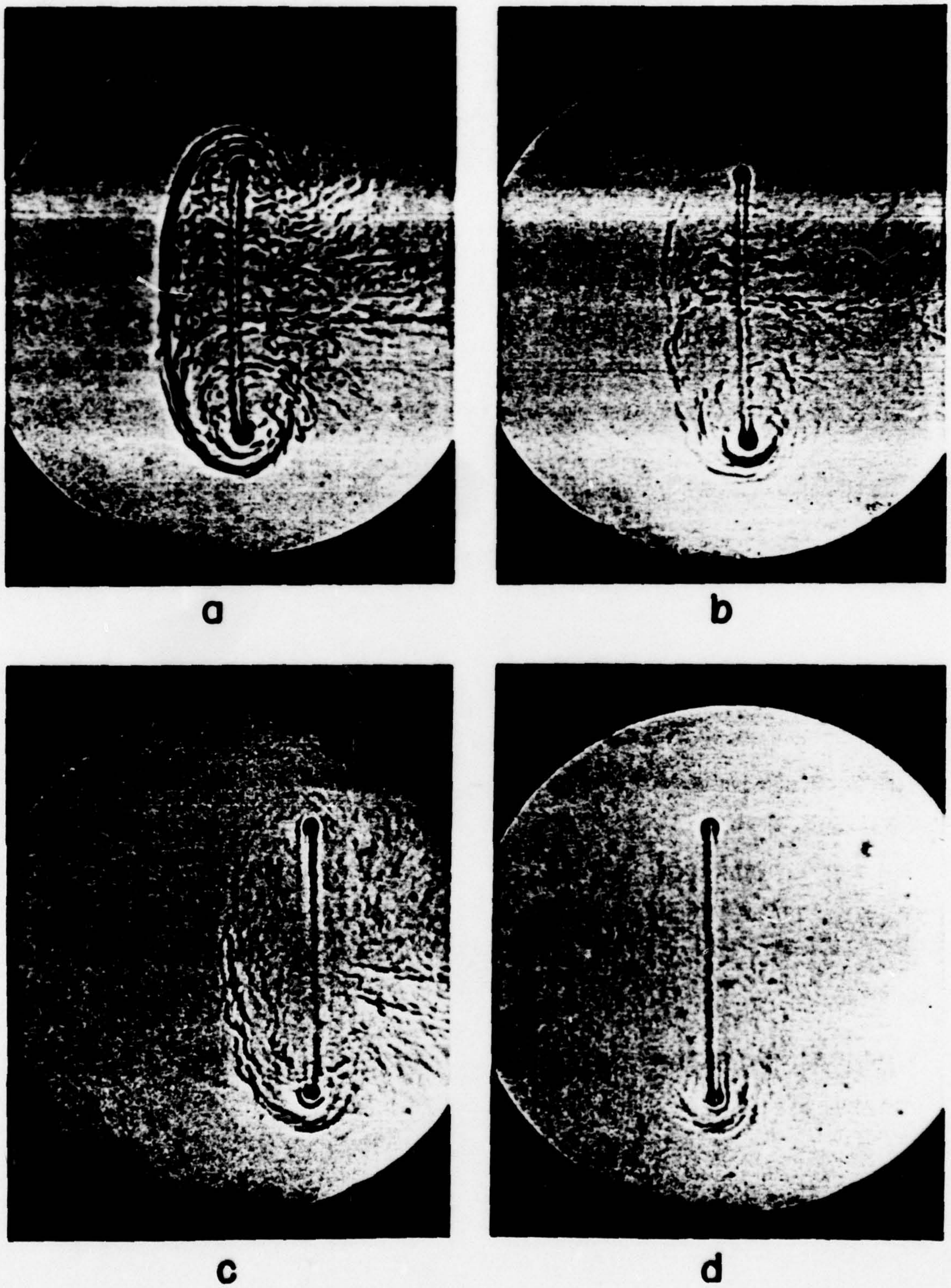

Figure 8

Vortex Ring Generated by 2.5 cm Driver

a. 10 cm Location b. 20 cm Location

c. 30 cm Location d. 40 cm Location

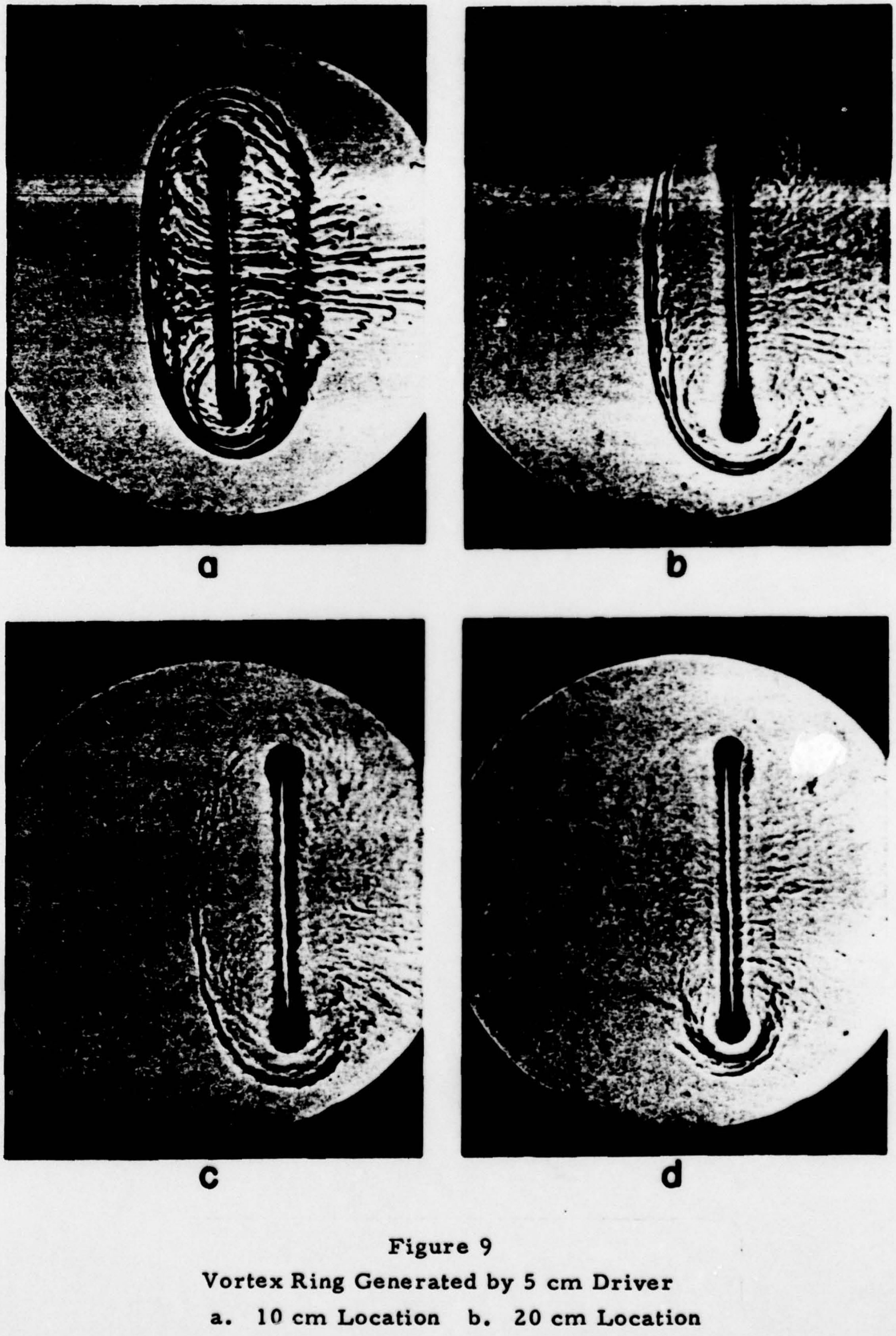

Figure 9

Vortex Ring Generated by 5 cm Driver

a. 10 cm Location b. 20 cm Location

o. 30 cm Location d. 40 cm Location

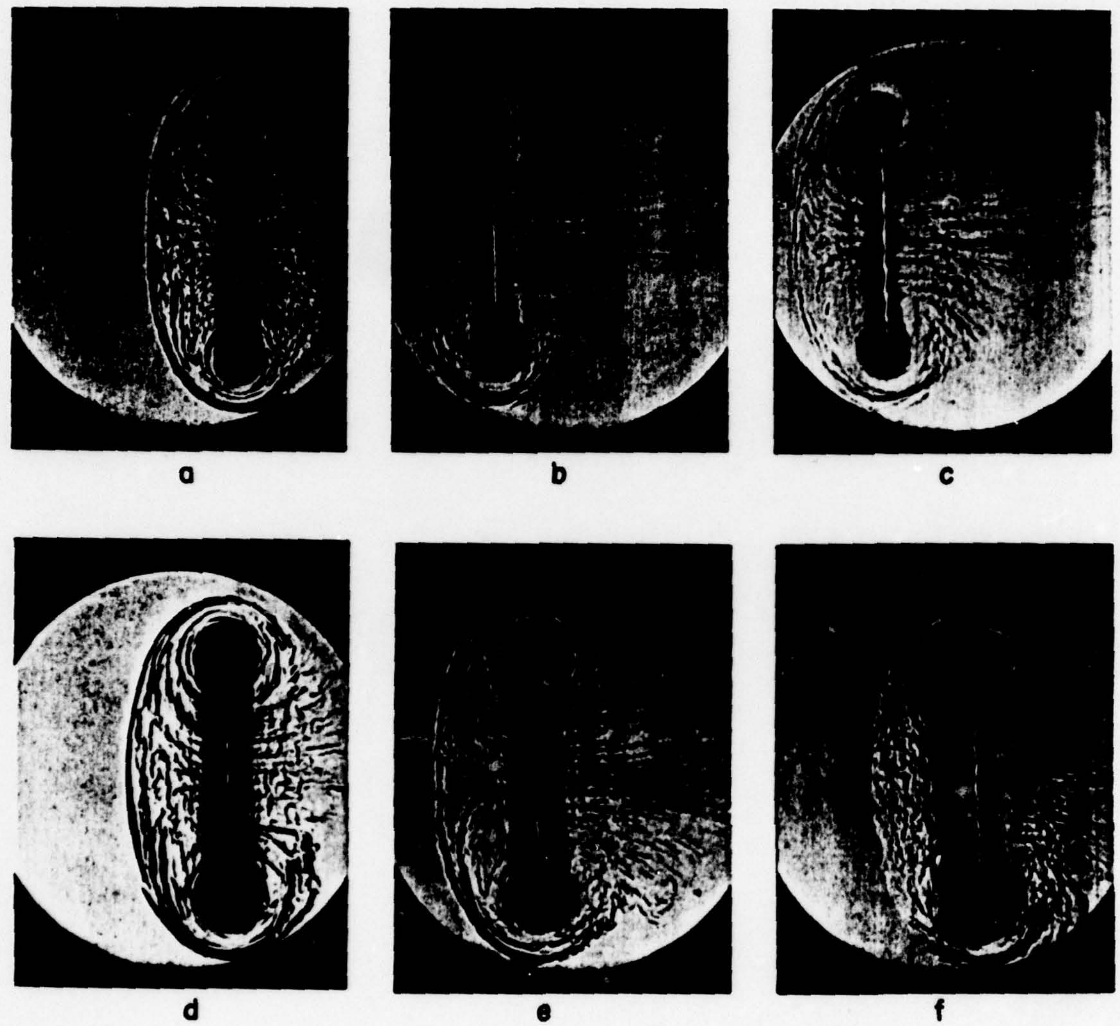

Figure 10

Vortex Ring Generated by 10 cm Driver
a. 20 cm Location b. 30 cm Location c. 40 cm Location

Vortex Ring Generated by 15 cm Driver
d. 20 cm Location e. 30 cm Location f. 40 cm Location

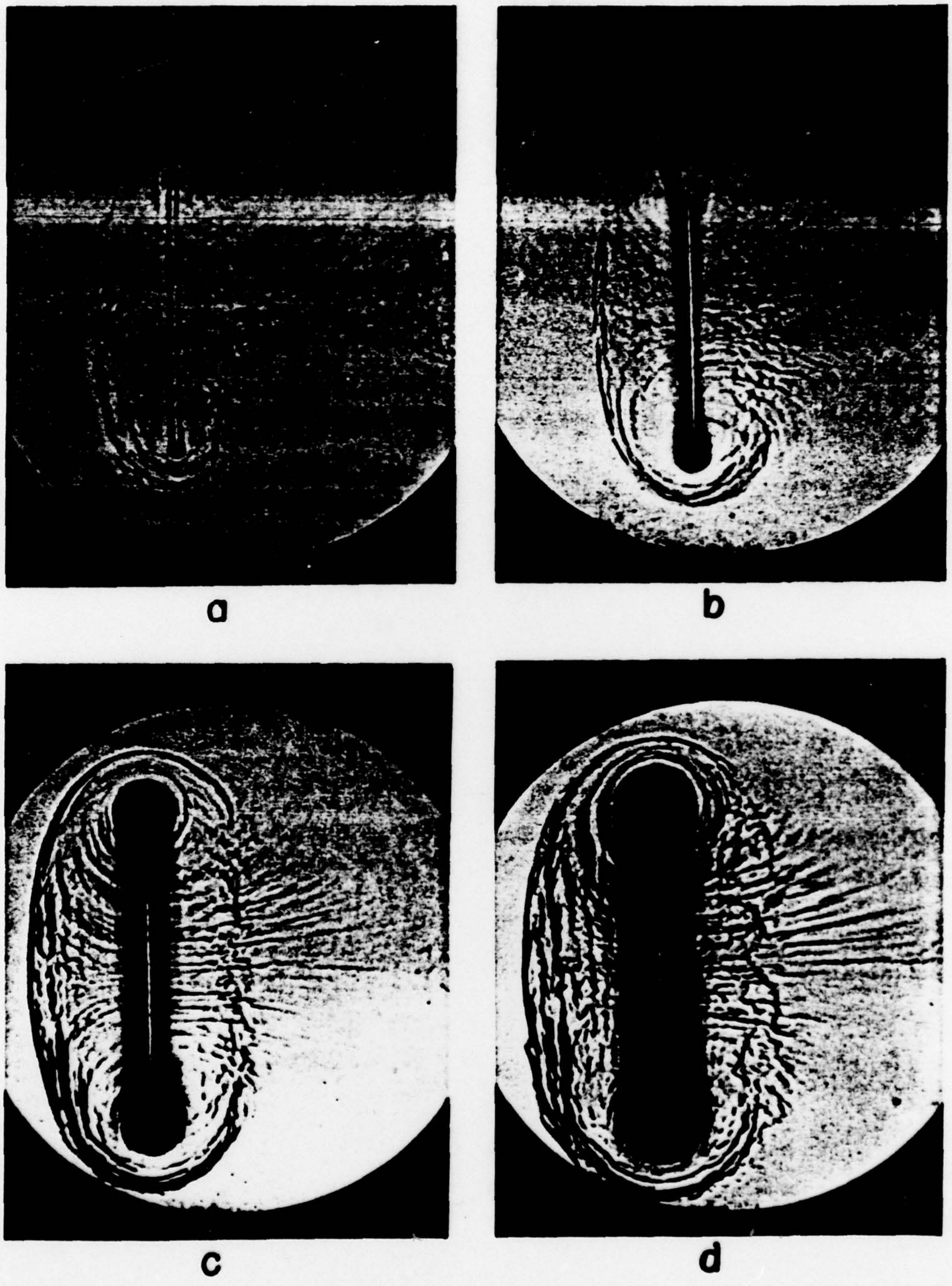

Figure 11

Vortex Rings at 20 cm Location

a. 2.5 cm Driver   b. 5 cm Driver

c. 10 cm Driver   d. 15 cm Driver

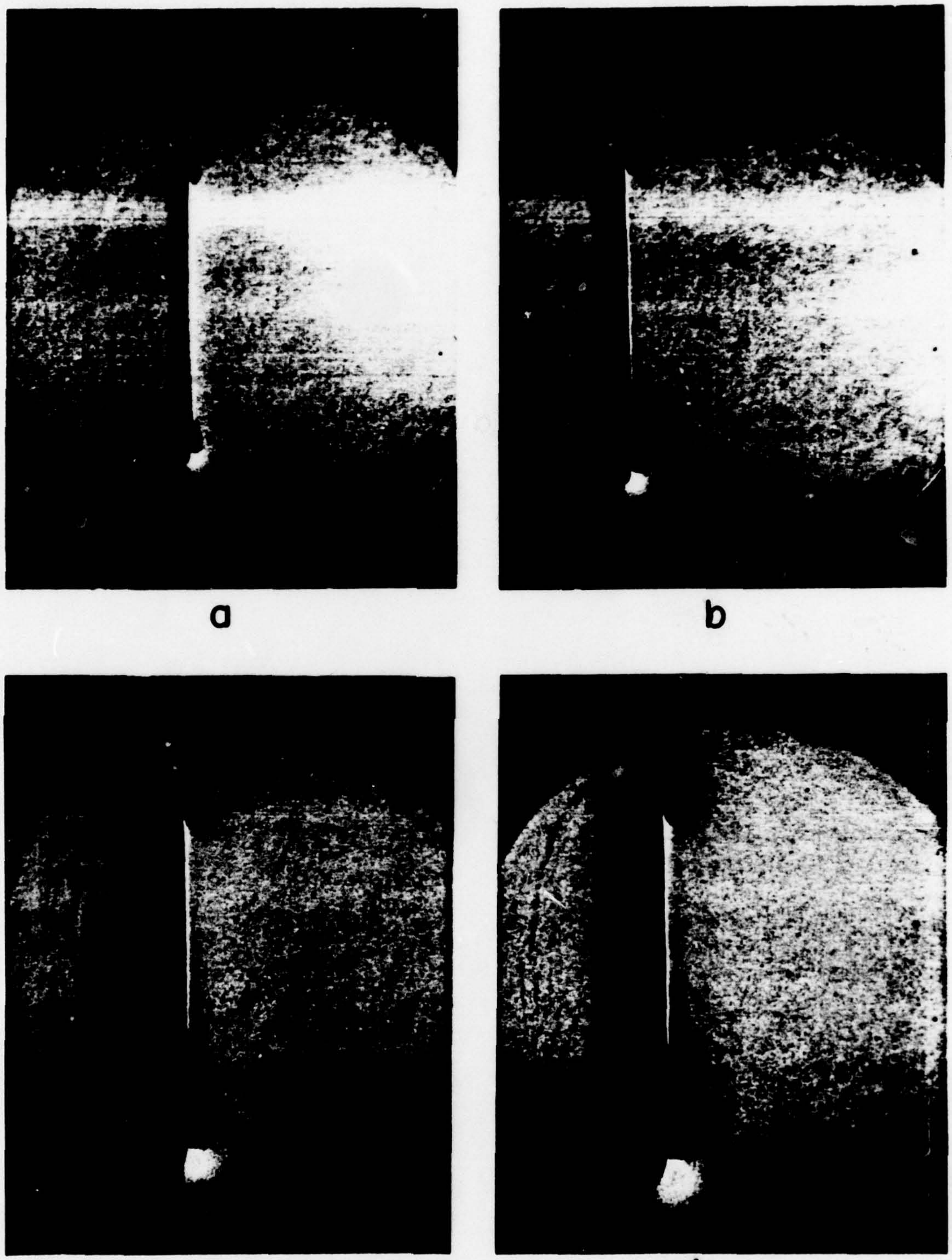

Figure 12

Vortex Rings at 20 cm Location

a. 2.5 cm Driver b. 5 cm Driver

c. 10 cm Driver d. 15 cm Driver

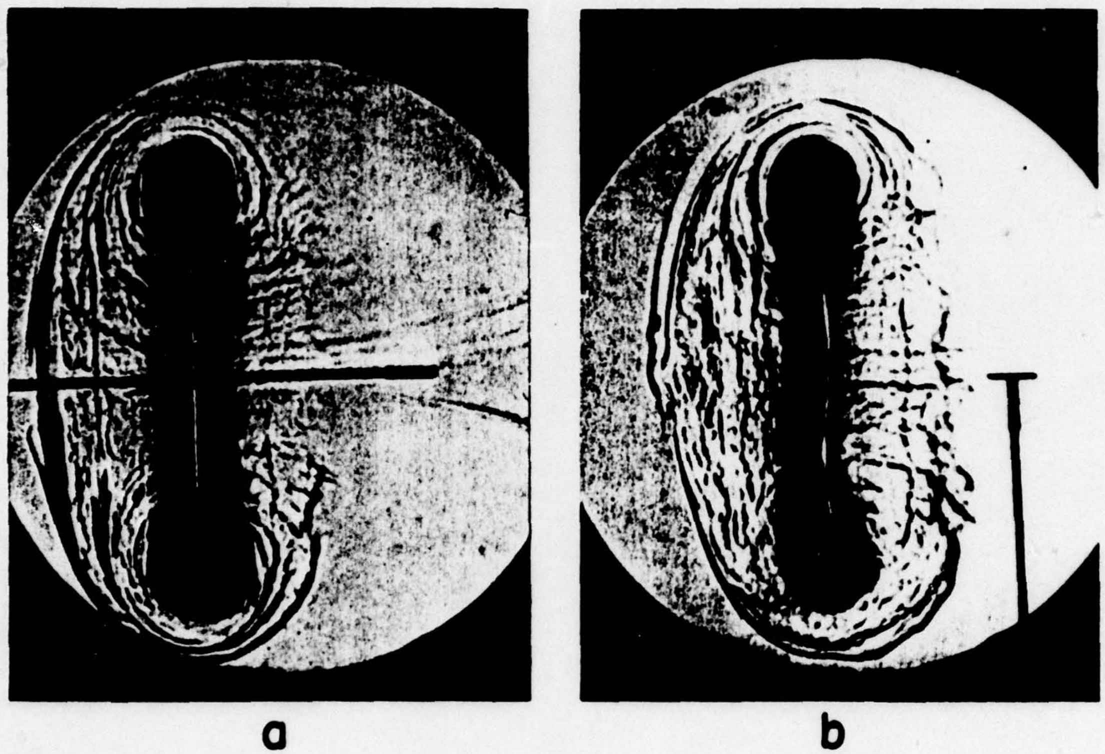

Figure 13

Vortex Ring Generated by 15 cm Driver

20 cm Location

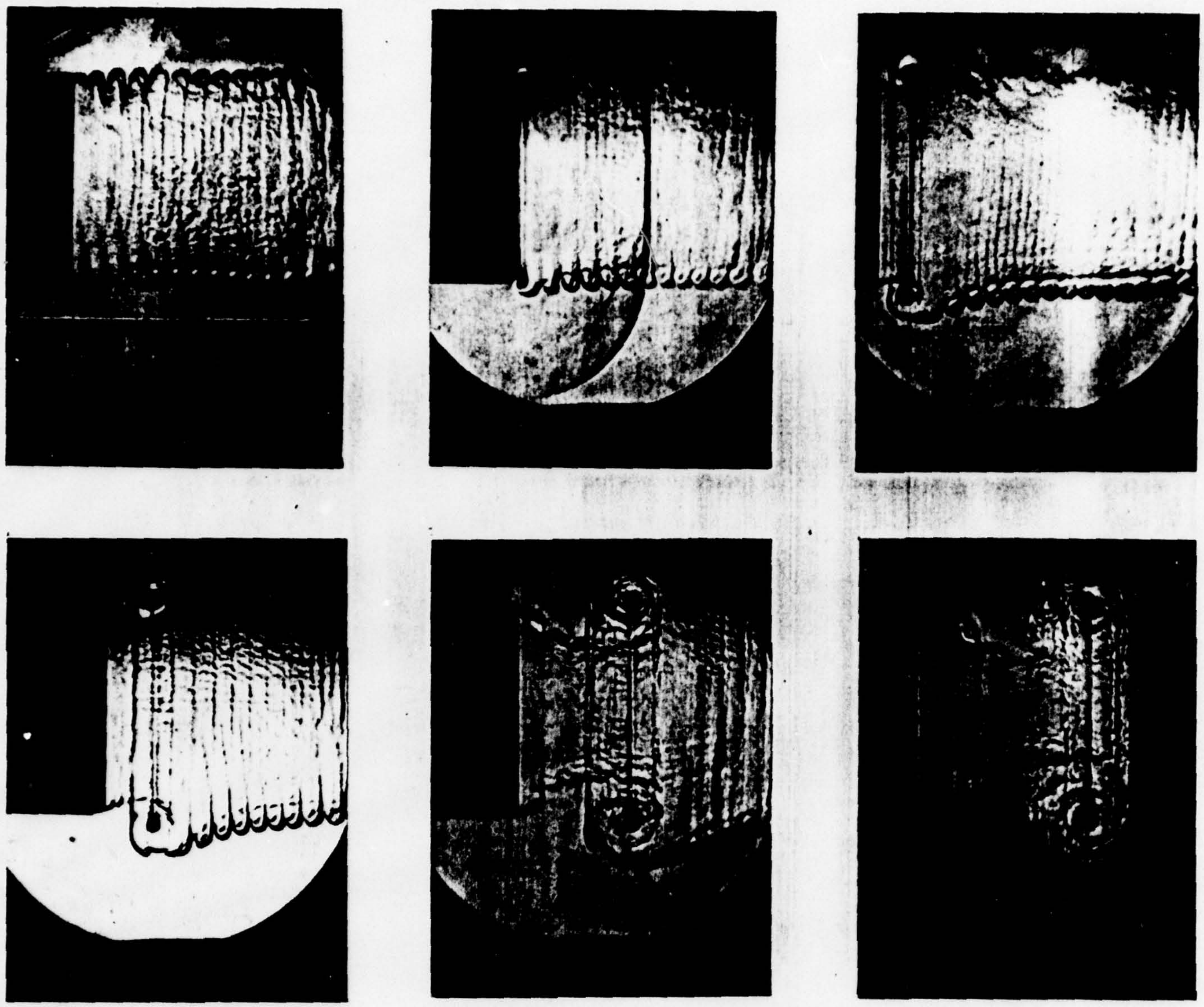

Figure 14

Vortex Ring Formed in the Wake of a Moving Tube

Driver Length 2.5 cm   Tube Speed 14 Meters/Second

a. No shock wave   b. 4.4 ms   c. 4.7 ms

d. 5.3 ms   e. 5.9 ms   f. 6.4 ms

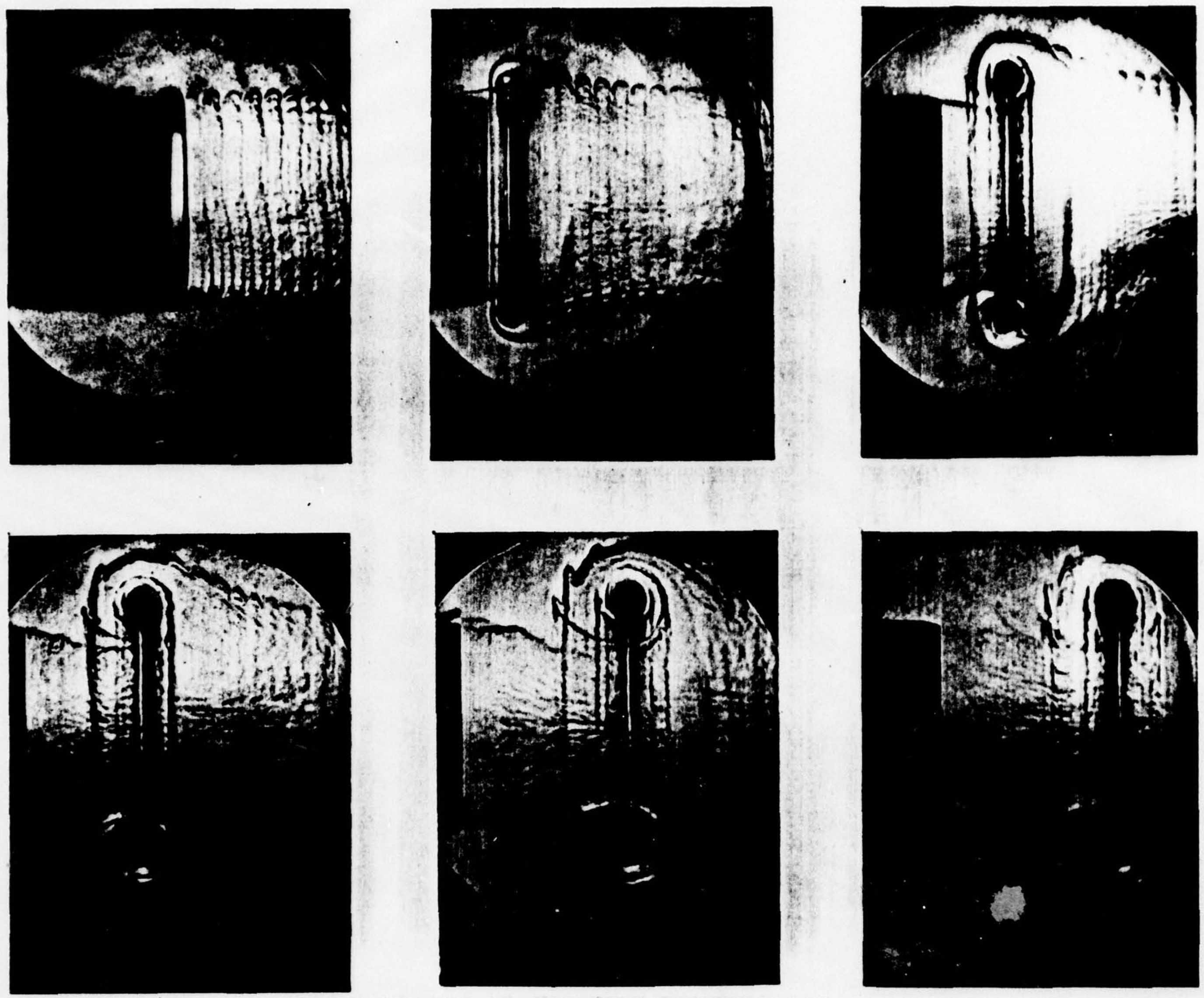

Figure 15

Vortex Ring Formed in the Wake of a Moving Tube

Driver Length 10 cm   Tube Speed 14 Meters/Second

a. 4.3 ms	b. 4.5 ms	c. 4.8 ms
d. 5.0 ms	e. 5.4 ms	f. 5.6 ms